Hazard management lessons learned through mapping and assessing landslides triggered by Hurricane Mitch

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1. Abstract

Landslides are a serious concern in steepland regions where powerful storms are common and human settlement is expanding. The hazards associated with the combination of topography, climate, and land use was starkly evident in the catastrophic losses associated with landslides triggered by the 1998 Hurricane Mitch which was centered on Nicaragua and Honduras. Aerial photos taken within a month after the hurricane offer a unique opportunity to assess landslide hazard associated with slope and cover type. Landslides were identified from these black and white aerial photographs using interpretation keys. We applied this approach to document landslides and associated gully formation in two provinces in Northwest Nicaragua that occurred during Hurricane Mitch. Initiation of landslides on 40% to 65% slope forested land was significantly lower than on land where the trees and shrubs had been removed. Furthermore, the area disrupted by any particular landslide tended to be strongly influenced by the slope and land use characteristics of where the landslide began. Landslides originating on steeplands cleared of trees and shrubs were more likely to be larger than were landslides originating on similarly sloped forested lands. Terracing treatments (rock walls, vetiver grass or tree barriers, or a combination thereof) installed on contour with the slopes were effective at reducing the initiation of landslides within the terraced area, but there were many instances of rock, vetiver grass and agroforestry alley cropping systems being destroyed by landslides originating above the terraced area. Maintaining forests upslope and adjacent to the terraced fields, or terracing to the top of the catchment, was an important consideration influencing whether the terraces held or failed during the extreme rainfall events associated with Hurricane Mitch.

2. Introduction

Approximately 800 million people directly depend upon the 1 billion ha of land classified as tropical steeplands (slopes greater than 30%) (Purnell 1986). Many of these tropical steeplands are also susceptible to high intensity monsoonal rains and have soil characteristics that present a host of challenges to maintenance of soil fertility and stability (Lal 1990). As human populations continue to rise in these ecologically sensitive regions there has been increasing pressure to clear and cultivate steeplands that have historically been forested, resulting in an increase in landslide hazard reflected in soil loss rates of 100 to 200 tons ha^{-1} yr^{-1} on cultivated steeplands (Pimentel et al. 1995). Often the infiltration rates on tropical steeplands are high, but the steep slopes combined with a low plasticity index value along soil/bedrock interface lead to shear failure. Consequently, most of the soil movement off steep slopes tends to be associated with mass-wasting rather than interrill erosion (Thurow and Smith 1998). Most published research on tropical steepland erosion rates have been conducted on plots that are too small to embody mass-wasting processes, thereby evaluating the soil conservation effectiveness of treatments relative to interrill and, perhaps, rill erosion but not accounting for the much greater erosive forces associated with landslides. Thus, some studies of conservation treatments such as mulching instead of burning during field preparation for planting, report that mulching is effective at reducing interrill erosion, but research conducted at a field catchment scale demonstrates that mulching is not effective at preventing mass-wasting (Thurow and Smith 1998, Thurow et al 2004). Terracing using rock walls or live barriers installed on contour of a slope is commonly used in an attempt to reduce landslide hazard throughout the steepland regions of the world (summarized by Toness et al. 1998).

The extent of landslide impact associated with extreme rainfall events, such as caused by Hurricane Mitch which struck Central America in 1998, can be devastatingly costly in terms of both economics and loss of life (IADB 2000). The combination of slope and vegetation cover is an important factor determining the amount of area affected by landslides. For example, Perotto-Baldiviezo et al. (2004) documented that Hurricane Mitch was associated with landslides affecting 14% of the steepland area (>30% slope) if the soils were bare, approximately 6% of the steepland area affected if planted with agronomic crops, and <1% of steepland area affected if the steepland was forested. While such storm events are rare they are important events that should be part of prudent development policy since they are a regular, albeit unpredictable, characteristic of the region's climate regime (e.g., in the three years proceeding Hurricane Mitch there were seven storms in the Caribbean that each produced at least 430 mm of

rain).

The effectiveness of terraces at reducing landslide hazard is difficult to assess from reports in the scientific literature because a number of germane considerations are often not reported. For example, correct implementation of construction specifications (e.g., was the distance between the contour barriers appropriate for stabilizing the slope) is extremely important for terraces to be effective (Sheng 1977), but it is not uncommon on rural steeplands throughout the world to see terrace structures that do not adhere to such specifications. Also, the degree of maintenance of the terrace structures by the farmers is variable, a fact that compromises their effectiveness especially as they age (Holt-Gimenez 2002). Another factor that is often not included when terrace failure is reported is whether the landslide that damaged the terraces originated within the terraced field or upslope of the terraced fields. The objective of this paper is to assess the degree to which the point of landslide origin influenced landslide impact on terraced fields.

3. Methods

The study area was the steeplands of the Pacific Volcanic Range within a 40 km radius of Chinandega, Nicaragua. Andesites, basalts and pyroclastic rocks are the dominant lithology. This region was originally forested, but is now extensively fragmented by active cultivation (primarily maize, sorghum, and beans) or various stages of fallow succession. Annual precipitation averages 1,884 mm with 94% of this total occurring between May and October. Hurricane Mitch affected the study area from October 21 to 31, 1998. The total rainfall recorded during this period in Chinandega was 1612 mm, with 1420 mm of rain from that storm falling between October 28 and 31.

For this study we used the black and white aerial photos acquired by the US Air Force at 1 to 5 meter nominal spatial resolution. These post-damage photos were obtained from the USGS EROS Data Center (Sioux Falls, SD) in TIFF format along with an index showing the approximate location of the center point of each photo. Since there was overlap between the photos in each flight line, we included every other photo for this study. Photos were displayed one at a time and landslides were interpreted based on shape, size, texture, association and pattern. A digital elevation model (DEM) for Nicaragua was downloaded from the USGS website and this 30 m raster dataset was used for calculating slope. Our study focused on the portion of the landscape that had a slope ranging between 40% and 65% and had a cover-type that was either forest or land that was cleared of most trees and shrubs.

Each landslide event, was categorized as small (<15 m) or large (>15 m) along with the corresponding land cover type. Our analyses focused on the effective area of each photograph where the image distortions were minimal. Furthermore, we included only those landslides for which the point of origin could be located within the photographs. We interpreted 30 photographs; within each photograph the number of landslides recorded ranged between 2 and 5. The resulting information was tabulated in a 2 x 2 Kappa agreement matrix.

The Kappa coefficient of agreement (K-*hat*) combines information about the diagonal elements (where there is complete agreement) and off-diagonal elements (where there is no agreement). This metric is widely used for assessing the agreement between land type classes derived from remotely sensed data and the true land type data collected from the field (Congalton 1991). The possible outcome of K-*hat* ranges from -1 to +1. The hypothesis being tested in our analysis was that the length of the landslide would be small (<15 m) if it originated in a forest, but the length of the landslide would be large (>15 m) if it originated in a recently cultivated area. Therefore, if the samples reflected a perfect agreement with this hypothesis the K-*hat* would be +1. If the relationship was the exact opposite of what was hypothesized the K-*hat* would be -1. If there no relationship at all between these category variables the K-*hat* would be 0.

4. Results and Discussion

Landslides were readily apparent on the 1 m to 5 m resolution aerial photos based on the color (exposed soil with almost no vegetation compared to the surrounding area), shape and image texture associated with debris flows. On land with a 40% to 65% slope, there was a strong relationship (K-*hat* = 0.82) computed for the agreement matrix between the magnitude of landslides and the land cover type where the landslide originated (Table 1). Small landslides were mostly (87%) confined to originating within forested areas, whereas almost all of the large landslides (96%) originated on fields that were cleared of most of the trees and shrubs. Thus while landslides did occur in forests, affecting about 1% of the forest area, they rarely posed a threat to downslope activities. In contrast, landslides that originated in cleared fields had a much greater chance of extending downslope.

Table 1 Agreement matrix for land with 40% to 65% slope, comparing the cover type in which origin of landslides occurred with the length of the associated landslide

Landslide	Cover Type		
Length Class	Forest	Cleared Fields	Total
Small (<15 m)	40	7	47
Large (>15 m)	2	52	54
Total	42	59	101

Of 38 terraced fields, none showed signs that a landslide had originated within the terrace block, while 12 (32%) were impacted by landslides that originated on cleared fields upslope of the terraces. In many cases, terraces were built starting from a point of logistic convenience such as a road or village. When cleared fields were present upslope of the terraces a landslide originating on the cleared fields was likely to build momentum that would overwhelm the integrity of downslope terrace structures.

5. Management Implications

The literature on the effectiveness of terraces at minimizing landslides impacts is mixed (summarized by Toness et al. 1998), in large part because such analyses typically fail to verify that 1) the terrace spacing and construction were appropriate, 2) the terraces were properly maintained, and 3) landslides originating upslope of the terraces result in destruction of the terraces. The objective of this paper was to explore this third concern confounding interpretation of terrace effectiveness. Analysis of landslides on the 40% to 65% steeplands of Nicaragua indicates that the integrity of terrace structures was maintained throughout the exceptional rainfall events associated with Hurricane Mitch. Thirty-two percent of terraced fields reflected some damage by landslides, but in each case the point of landslide origin was on land cleared of trees and shrubs that was upslope of the terraces. Landslides that originated in forest were generally small and did not have the chance to build the momentum for extensive downslope disturbance. Forest protection at the headwaters of catchments is therefore very important (Haigh et al. 2004) to prevent the initiation of serial downstream environmental disruptions (Thurow and Juo 1996). These data indicate that it is important that the terraces either extend to the top of the catchment, or else that the top portion of the terrace block be bounded by forest.

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